New 3D model based urban energy simulation for climate protection concepts

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ABSTRACT

Climate protection concepts for cities and regions are designed to establish CO_2 emission baselines and develop measures for climate change mitigation. Up to now such concepts were based on aggregated consumption and emission data and only qualitative estimations of the effect of measures were possible. To better quantify the impact of mitigation measures, a large amount of data on the building stock is needed. Very powerful analysis possibilities for an energetic and economic evaluation of scenarios arise, if continuously growing data stock organized in geographical information systems are combined with simulation models of buildings and energy systems. In this work, 3D data models in CityGML format of the entire building stock of Ludwigsburg, a German county with 34 municipalities, were used and enriched with building's year of construction and its function to allow an automatized quantifying the climate protection indicators. In this regard, the heating demand of each individual building in the region in the current state and after two refurbishment scenarios are calculated. In addition, the local solar photovoltaic potential is determined, as the exact size and orientation of each building surface is in the 3D model available. Besides, some new methodologies are described to better quantify the costs and benefits of CO_2 mitigation strategies on a local or regional level and to support decision making.

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1. Introduction

Many cities and regions are committed to develop climate protection concepts and have set ambitious CO_2 reduction targets. In many international urban networks information and best practice examples are exchanged, such as the Cities for Climate Protection Program (CCP) established in 1993 or the C40 network founded in 2005. Local authorities are crucial actors in climate change mitigation, as they can regulate, advise, and facilitate action by local communities and stakeholders, and have considerable experience in addressing environmental impacts within the fields of energy management, transport, and planning [1]. A precondition for action is a model for local energy use and greenhouse gases, because without detailed information on urban energy flows strategy development and management of measures is not possible [2].

The determination of the baseline energy consumption and CO_2 emissions in climate protection concepts is today mainly based on aggregated statistics or average values. Whereas, in a bottom up approach specific values related to the building space and the building footprint as a function of buildings' type and age are used to determine the status quo of consumption [3–5]. Such approaches have the advantage to include occupant behaviour and macroeconomic and socioeconomic effects in the consumption, but its reliance on historical consumption information does not necessarily allow projections for the future.

It is a major challenge to quantify and predict the urban energy demand [6]. The two main modeling strategies for building energy consumption are top-down and bottom-up methods [7,8]. Depending on the input data and structure, bottom-up methods apply either statistical or physical models [9]. The former has some limitations, like the need of a large sample group, and not specifying the impact of the energy conservation measures, which is important for urban energy strategies. Modeling the thermal energy consumption with a physical approach is based on algorithms like quasi-steady state or dynamic hourly models using geometrical and semantic data [10].

Urban energy modeling is computationally intensive, due to the increasing level of detail and amount of building data, such as construction and usage data, attached. Either the processing power can

Nomenclature

El.	Electricity
GIS	Geographic information system
ICT	Information and communication technology
ITCS	Industry, trade, commerce and services
PV	Photovoltaic

be improved by implementing cloud-based or parallel computing solutions [11] or the urban models can be simplified [12]. A range of simplified tools are available with different scope of application and functionalities [13].

The use of GIS is very useful for integration and structuring the large urban data set [14,15]. Virtual 3D city models generated from airborne laser scanning or photogrammetry technologies can provide an excellent dataset for bottom-up physical modelling, storing geometrical and semantic data of entire cities [16]. Based on such city models, several urban heat demand analyses have been recently carried out in some European cities like Berlin [17,18], Karlsruhe and Ludwigsburg [19], Trento and Ferrara [20].

Modelling a growing number of cities, regions and even countries (Germany), virtual 3D city models represent a powerful support for public authorities and engineering companies to tackle the urgently required energy transition. Among the 3D city model formats, the open standard CityGML stands out as the reference, providing an excellent and flexible spatial-semantic data structure for 3D geospatial visualization, multi-domain analysis and exploration [21,22]. The CityGML data model is the basis of the new urban energy simulation platform SimStadt developed at the University of Applied Sciences Stuttgart during the last years. This platform aims to support urban planners and city managers with defining and coordinating low-carbon energy strategies for their cities, with a variety of multi-scale energy analyses. The platform integrates simulation algorithms and makes it possible to test the effects of various data sources [23].

The input data quality is crucial for the accuracy of the results and several European directives and projects dealing with urban data management are working on this issue, like INSPIRE [24], 2007 or SUNSHINE [25]. Investigating the impact of the different input variables on the result accuracy enables the identification of the most influential input data and the analysis of data uncertainty [6,26]. As a result, intelligent and adequate data collecting strategies can be designed, assigning resources to the most important parameters, while parameters with minor influence can be assessed with coherent benchmarking values.

A study of Nouvel et al. [27] investigates the influences of data quality on the urban energy platform used in this study. According to this study the most affecting data is the year of construction as well as refurbishment of the building, base on which the thermal properties i.e. the ratio of the heat transmission of the building is determined. Applying a high quality of such a data for the heat demand simulations can results in a more accurate calculation of the contributions of renewable energies to cover this demand. This requires the simulation of the energy provided by solar energy conversion system and to relate this produced energy to the demand of each building in question. This is particularly important when solar thermal energy use, which is currently only directly used by each building and usually not fed into heat distribution grid, is considered. But also for photovoltaic electricity generation it is increasingly important to determine the level of self-consumption in each building, as this determines the economics of the system operation.

The scope of this paper is to employ an automated urban energy platform on a case study in Ludwigsburg, a German county with 34 municipalities, for developing a measures and initiatives for a climate protection concept in this city. Firstly, the automated method of heat demand calculation in this platform is explained. Then the case study is explained and the location-specific method of electricity demand and CO2-emission are described. The electricity demand for Ludwigsburg is extracted from concession bills, where available and otherwise is evaluated using typical statistical consumption data based on net floor area and building's usage. In the next section, the results of the platform for the heat demand of Ludwigsburg are presented. The heat demand is simulated from geometry and building construction information for each of almost 177,000 residential and non-residential buildings and then building efficiency scenarios with various insulation standards were analyzed. Finally, two examples of measures or initiatives based on the platform results are explained, and it is shown how a climate protection concept has been developed based on these measures for Ludwigsburg, our case study. The PV potential analyses as a measure is calculated for each individual building. The method is explained in detail.

2. Heat demand simulation method and data requirements

The urban simulation platform SimStadt [23] is applied to investigate the current status of energy demand, evaluate prospective energy demand scenarios and serve as an advance base to design concrete measures for action.

Within the space heating workflow, the thermal energy demand is calculated for each building, where some basic data like year of construction, building usage as well as proper 3D geometry is available. Geometry data are provided in the CityGML data format, an open data model for spatial data exchange issued by the Open Geospatial Consortium OGC (OpenGIS® Encoding Standard OGC 12-019). CityGML can model buildings with 4 different Levels of Details (LoDs). LoD1 models buildings as a cube with flat roofs, whereas LoD2 adds the details of roof shape. In LoD3 the details of exterior surfaces like windows and doors are added and the last LoD models the interior surfaces as well. The workflows in SimStadt have the ability to work compatibly with the first two LoDs.

The 3D building model was provided by the State Agency for Spatial Information and Rural Development Baden-Württemberg LGL BW. These 3D models for the whole state were created based on stereo aerial photographs and laser scanning and are based on the real estate cadastre information system (ALKIS, 2013–2015). The 3D model includes 80% of the objects in LoD2 and 20% in LoD1. The data year of construction were provided by the company Nexiga.

To determine the space heating demand, weather data is also required. For the Ludwigsburg region, monthly values of irradiance and temperature were used from PVGIS_Database for the location of Stuttgart (Stuttgart-hour.tmy3).

The monthly energy balance is then calculated according to DIN 18599-2, a quasi-steady-state method. In SimStadt each building is considered as one zone, i.e. the space for which the monthly balance is calculated. The heat flow through the heat sinks and sources in the zone is summed up in an average-based for each month (Eq. (1)).

$$Q_{h,b} = Q_{sink} - \eta Q_{source} - \Delta Q_{C,b} \tag{1}$$

Where,

$Q_{h,b}$, is heat demand of building zone averaged over one month in (kWh),

Q_{sink}, is the sum of heat sinks in the building zone averaged over one month in (kWh),

Table 1

Assumptions for domestic hot water calculation as a function of building type.

Building Usage	Assumptions according to DIN 18599-10			Calculation
	Occupancy Density (m²/person)	Annual operation days	DHW-Usage Dependent (kWh/person.day)	DHW (kWh/m².a)
Residential	30	365	--	12[a]
Education	2.5	200	0.4	32
Office and administration	10	250	0.4	10
Retail	4	300	1	75
Hospital	14	365	6	156.4
Sport locations	5	365	1.7	124.1
Industry	20	230	1.8	20.7
Hotel	10	365	3.5	127.8
Restaurant and Coffee shops	1.2	300	1.1	275

[a] Not calculated, but available in kWh/m².a. in DIN 18599-10.

Table 2

Heat transfer coefficients of building components for status quo, medium and advanced standard.

Building component	U-Value status quo [W/(m²K)]	U-Value "medium" scenario [W/(m²K)]	U-Value "advanced" scenario [W/(m²K)]
Pitched roof	0.35–1.75	0.35–0.40	0.14
Flat roof/top ceiling	0.23–1.21	0.13–0.74	0.11
Wall	0.3–1.87	0.18–0.39	0.11–0.14
Floor	0.31–2.66	0.23–0.49	0.18–0.26
Window	2.7–4.3	1.3–1.6	0.8–1.25

Q_{source}, is the sum of heat sources in the building zone averaged in one month in (kWh),

$\Delta Q_{C,b}$, is heat transferred from the building elements into the building zone during periods of reduced operation at weekends and during holiday periods, averaged over one month in (kWh),

η, is the monthly utilization factor of the heat sources.

all heat sources and sinks i.e. heat flow through transmission, ventilation internal and solar transfers are calculated for each month, considering the average monthly temperature and global radiation. The temperature difference between set-point temperature inside the building and monthly averaged external temperate affect the heat flow through transmission and ventilation. The internal gains from persons or appliances such as computer or lighting differ according to building function for example residential buildings have different internal gains as offices. This is explained in detailed in Table 3. The window sizes as well as average monthly global solar irradiance affect the heat flow through solar radiation. The annual heat demand is the sum of the monthly heat demands over a year (DIN 18599-2).

Domestic Hot Water (DHW) is also considered for each building in addition to space heating. DHW is extracted from the daily area specific energy demand for DHW specified for each building usage type which is provided by German standard DIN 18599-10. The Energy Reference Area (Eq. (2)) calculated according to the German Energy Saving Ordinance is used for all building usages (EnEV 2014, § 1.3.3, Anlage 1).

$$If hs \in [2.5m; 3m] : An = 0.32 * V \text{ else} : An = \left(\frac{1}{hs} - 0.04\right) * V$$

(2)

hs: Average story height, m

V: Heated volume, m³

An: Energy Reference Area, m²

Annual operating days and Occupancy density (m²/person), defined for each building usage type in the DIN 18599-10, are applied for the annual domestic hot water calculation. Table 1 shows the usage-related parameters assumed in DHW calculation. It is assumed that the water needs to be warmed up from 10 °C to 45 °C.

The simulation results are then classified in three building categories residential, public and industry, trade, commerce and services. Municipal concession bills for total electricity and gas consumption were used to compare the simulated results with real consumption.

Beside the status quo analysis of the current energy needs of districts, two refurbishment scenarios i.e. "Medium" and "Advanced" are analyzed in SimStadt. Different building parameters are used for each scenario regarding the building physics characteristics such as heat conductivities and capacities of the different construction layers. For this all buildings are sorted into categories like single-family houses, multi- family houses etc. base on their year of construction. The data base uses a building typology developed by the Institute IWU [28] in Germany. The assumption for the "Medium" scenario is a standard refurbishment level corresponding to the German Energy Saving Ordinance 2009. The assumption for the "Advanced" scenario is a level of refurbishment which is similar to standards of passive houses, but without a ventilation system with heat recovery. Table 2 lists the heat transfer coefficients of building components used for the simulation of the two refurbishment scenarios. The values are applied depending on the building type and year of construction.

The simulation can be performed with different annual rates of refurbishment. For a given refurbishment rate, the buildings are then selected stochastically from different categories and year of construction. It is however possible to change these constraints in SimStadt manually if desired. The heat demand simulation is applied to the case study of Ludwigsburg for developing climate protection concept. The electricity demand and CO2-emission data are

3. Case study integrated climate protection concept of county Ludwigsburg

The district of Ludwigsburg is located in the South-West of Germany with a total population of 353.042 inhabitants (2013). This number represents about 5% of total population of the German federal state Baden-Württemberg. The total surface of the rural district is 68,682 ha with more than 54% used agriculturally, 18% forest area, 24% settlement and traffic area and 4% of the surface is water or other landscapes. The district of Ludwigsburg is the third largest in Germany and 34 municipalities took part in the climate protection concept. For the analysis about 83.000 individual buildings were considered. The building stock is rather old with 75% of all building built between 1919 and 1978 and only 4% after 2002, making

refurbishment strategies a crucial element for CO_2 mitigation. The majority of the simulated buildings in district of Ludwigsburg are single-family houses and row houses (74%). 21% are multi-family houses and 5% public and commercial buildings. The assignment of the building usage is based on the main use of the building, which is part of the official real estate cadastre information system (ALKIS). Twelve different building usage types are recognized among the simulated buildings.

The integrated climate protection concept has three main goals:

- The first purpose is to determine potentials to reduce emissions and to design innovative projects to decrease or even avoid CO_2 emissions. This requires an energy status analysis to ascertain strengths and weaknesses. Laying the foundations for continuing CO_2 monitoring and determining the potentials of renewable energies shall be ensured too.
- Another objective is to issue a realistic and viable package of measures forming a basis for a financing concept.
- Thirdly, the rural district of Ludwigsburg strives to become climate-neutral until the year 2050 and to reduce the total CO_2 emission per capita in the county of Ludwigsburg below 2 tons.

To quantify both the energy efficiency and building integrated renewable potentials the new methodology of using 3D city models has been applied and is discussed in this paper.

3.1. Electricity demand determination

The concession bills of each municipality were the basis for the calculation of the electricity demand. If available, the concession bills from 2013 were applied, if not from 2012. To take the decentral electricity generation by photovoltaics and cogeneration systems into account, 10% additional consumption was added to the aggregated total values.

The types of customers from the concession bills were associated with the following sectors:

- tariff customers → private households
- tariff customers low load → trade, commerce, services and industry
- special customers" → partly from trade, commerce, services, industry and from the public building sector
- concession free → partly trade, commerce, services and industry and from public buildings

If no concession bills were available or the assignment of consumption to the sectors was not possible, the electricity demand was calculated by using area-related parameters for

the different usage categories. The net floor area which is required was determined in the context of the heat demand calculation. All values are taken from the German Industry standard "consumption characteristics for buildings; Heating, electricity and water" of VDI 3807 Sheet 2 and were partially adapted by own project experiences.

3.2. CO_2 emissions calculation

The CO2 equivalent emissions related to the heat and electrical demands have been also calculated, based on the related consumptions and CO2 equivalent emission factors. These factors indicate how much grams CO2 equivalent (considering the effect of all greenhouse gases) are emitted to the environment per kWh consumed energy.

The CO2 equivalent emission factor for the electrical demand is considered in the entire county of Ludwigsburg equal to the German electrical grid emission factor of 559 gCO2/kWh (2013).

The CO2 equivalent emission factor for the heat demand has been calculated specifically for each municipality depending on its own heat supply mix (considering centralized and decentralized heating systems) and the CO2 equivalent emission factors of each consumed energy carrier.

Information about the heat supply mix of each municipality comes from a study of the regional office for environment, measures and nature conservation of Baden-Württemberg for the year 2012. The CO2 equivalent emission factors of each energy carrier have been extracted from the Global Emission Model for Integrated Systems (GEMIS) database with 266 gCO2/kWh for gas, 320 gCO2/kWh for oil, 22 gCO2/kWh for biomass and 440 gCO2/kWh for coal based heating.

The lowest heating related CO2 emission factor for a municipality with 82% biomass fraction was 71,4 gCO2/kWh and the highest fraction (287 gCo2/kWh) goes to a municipality with 60% energy supply of oil and 30% of gas. The averaged CO2 Emission factor for the entire municipalities is 243 gCO2/kWh with average energy mix of about 40% gas and oil heating, 20% biomass.

4. Simulation results and validation

The simulation process was performed for each municipality of the Ludwigsburg district. Fig. 1 illustrates the heating demand of one of the municipalities in a building level.

Fig. 2 depicts that the total heat demand of the 34 municipalities is equivalent to 973,955 tons CO2 emissions for simulated buildings. The overall CO2 emissions are dominated by the residential sector followed by transport. In the Trade and Industry sector, the electricity related CO2 emissions are significantly higher than the heat related emissions. Interestingly, for Public buildings the CO2 emission from heat demand is more that electricity, considering that here only half of the public buildings are simulated. Therefore, initiations for heat demand reduction in public sector gets priority.

4.1. Total heating energy demand

To obtain the baseline scenario or status quo of the building sector's energy demand, buildings in each of the 34 municipalities was simulated using the monthly energy balance method. The total heat energy demand of the district is 4157 GWh/yr out of which 18% corresponds to domestic hot water. Fig. 3 shows the heat demand contribution of all communities which is directly correlated with the heated area.

The approach to validate the data of the heat demand simulation process was to use gas supply bills from the municipalities and compare them with the space heating demand simulated in SimStadt. The heat demand of not-residential buildings is not considered in this analysis as their use is very variable with a high uncertainty in the simulation results due to uncertain usage profiles. Each municipality is supplied by different type of energy carriers, one of which is gas, therefore only the gas proportion of the heat demand is compared with the measured gas consumption. For this comparison we have applied some assumptions:

1. The average conversion efficiency of the gas boilers of 85%. Therefore, the measured gas is multiplied by 85%, due to the heat lost in the heating system, and then is compared with heated demand out of SimStadt.
2. A climate correction factor of 1.09 for the year 2012 (taken from the German weather service (http://www.dwd.de). Since the heat demand depends on the weather data applied in the simulation, a weather correction factor or climate factor is used to make the heat demand, applying a tmy3 weather data, and heat consumption corresponding to the gas measured in year 2012 comparable. The weather correction factor is calculated based

Fig. 1. Visualization of the simulated heating demand using the 3D CityGML model for the municipality Hemmingen. Data provided by State Agency for Spatial Information and Rural Development Baden-Württemberg (LGL BW).
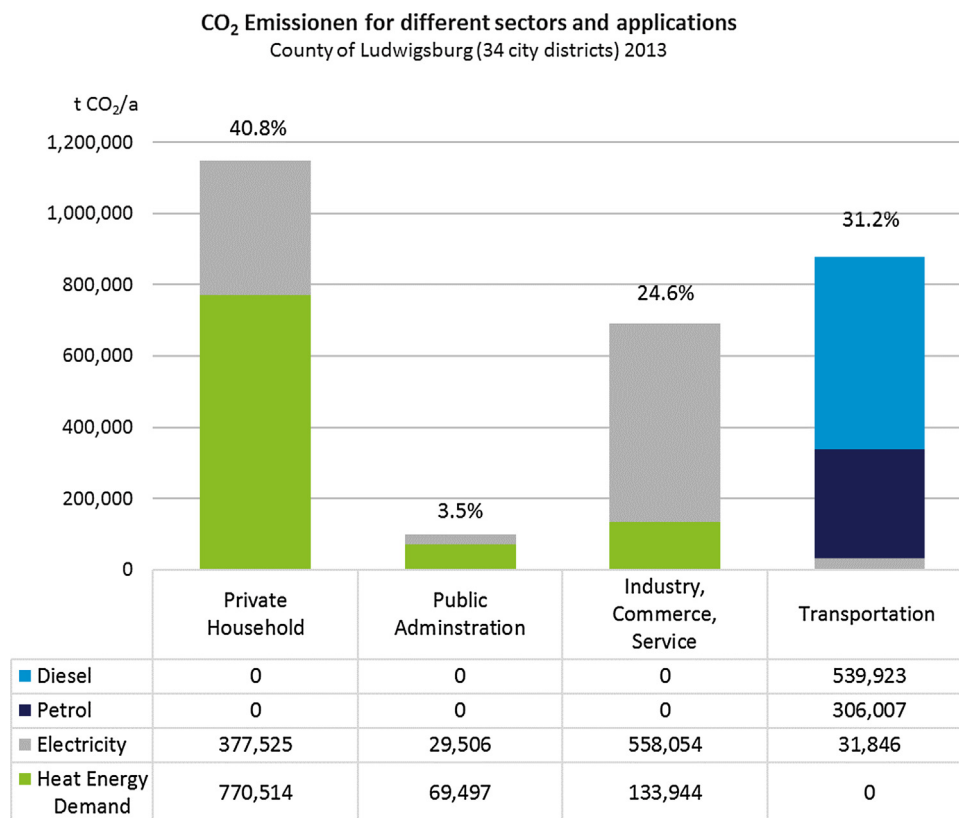

CO₂ Emissionen for different sectors and applications
County of Ludwigsburg (34 city districts) 2013

	Private Household	Public Adminstration	Industry, Commerce, Service	Transportation
■ Diesel	0	0	0	539,923
■ Petrol	0	0	0	306,007
□ Electricity	377,525	29,506	558,054	31,846
■ Heat Energy Demand	770,514	69,497	133,944	0

Fig. 2. CO₂ emissions related to the different sectors and energy carriers.

on the difference of the average daily outside temperature and the desired room temperature of a year. According to the German Weather service (http://www.dwd.de) the climate factor should be multiplied by the measured energy consumption. Therefore, in this study the heating consumption corresponding to the measured gas is multiplied to 1.09 and then is compared to the heat demand calculated in SimStadt.

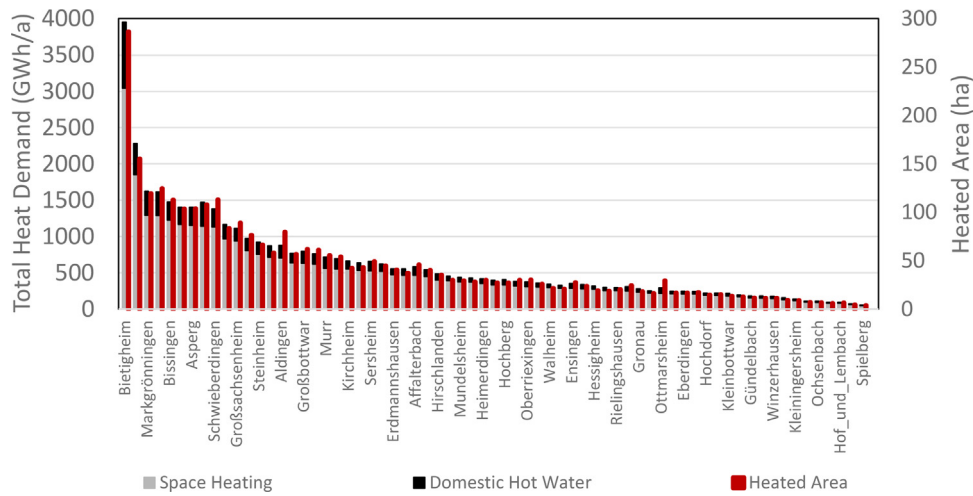Some municipalities are not supplied with gas and are left out from the comparison.

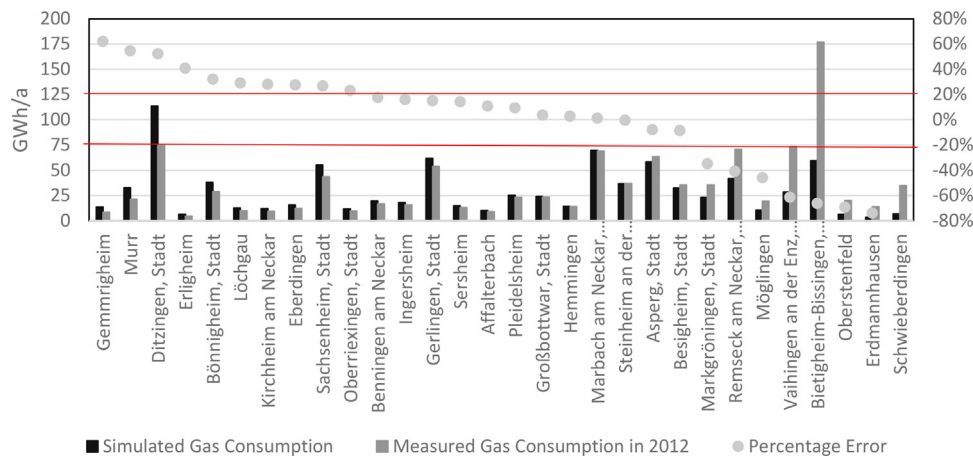**Fig. 3.** Total simulated annual heat demand of all buildings in the district of Ludwigsburg.

Fig. 4. Comparison of simulated and measured aggregated heating consumption of residential buildings with gas heating.

As Fig. 4 illustrates the deviation ranges between −20 to 20% for almost half of the municipalities. Higher errors might be due to inaccurate sources of information for the measured gas consumption. In fact, for some municipalities two different data sources for the gas consumption is available. For the communities with a high negative error, e.g. Vaihingen an der Enz or Bietigheim, the gas consumption from two different communal sources of information differed by more than 50%. This can justify the reason of extreme negative error in SimStadt. The reason of high positive error can be the unknown refurbishment status in the input dataset provided. The lack of refurbishment information is highly affecting the space heating demand. In addition, the number of building considered in the recorded gas consumption is not known, which makes the comparison more difficult. The measured gas consumption is only available for the entire municipality and cannot be attributed to the real supplied buildings. Therefore, more specific data of measure is required such as the number of buildings and preferably total heated area for which gas consumption is measured.

Lacking of adequate data is always a big issue in analysing urban demands. Here in this study we found out that even the statistical data from the communal sources of information can sometimes be thoroughly different from various sources, which makes the simulation validation in this study difficult. [27] has studied the influence of data quality on urban heating demand. They also validated this simulation platform for the region where detailed data of buildings and their gas consumption was available. They showed

that the total heat demand out of SimStadt for the studied city quarter differs only 10% from its total measured gas consumption. This error can raise up to 30% for a single building when the information about refurbished buildings in the city quarter is missing. In another study by [19], it is shown that SimStadt as an automated urban simulation platform works very well for the residential building sector, where the heat demand of the residential buildings resulted from simulation has a mean deviation less than 10% from measured consumption with a standard deviation of 18% in the studied city quarter in Germany, Rintheim.

Another source of differences between heat demand out of SimStadt and measured gas can be due to the user-related attributes. The non-residential sectors need more work for realistic assumptions in the modeling process. For them, specifically, the assumptions in user-related attributes requires a great afford. Proper user-related attributes such as internal gains, ventilation rates, daily and annual operation time of the building can lead to a more realistic heat demand for the building.

In our study, the values for these attributes are taken from a German standard, DIN 18599-10: 2011–2, however they might be very specific for some non-residential buildings, such as the industry Table 3 shows the values applied in this study. The set-point temperature is the desired temperature inside the building. The set-back temperature is the temperature which is set over night or holidays, as well as weekends, when the building is not in normal operation. The normal operation days in one month is determined

Table 3
Assumptions for usage-associated parameters in heat demand analysis, taken from DIN 18599-10:2011-2.

Building Usage	Annual operating day	Occupancy density (m²/person)	Temperature set point/set back (C°)	Healthy air change rate (m³/h/person)	Averaged daily Internal gain (W/m²)
Residential	365	30	20/16	40	2.1
Education	200	2.5	21/17	30	4.4
Office and administration	250	10	21/17	40	5.7
Shopping Center	300	4	21/17	20	6.5
Hospital	365	14	22	70	9.9
Sport	365	5	21/17	60	15.9
Industry	230	20	17	50	9.9
Hotel	365	10	21	30	5.2
Restaurant/Coffe	300	1.2	21/17	30	13
Hall	150	3	21/17	20	3.2
Event Location	250	10	21/17	20	2.6

based on the annually operating days. The heat demand of a month comprises of the heat demand over normal operation days and reduced operation days in month.

According to the building's thermal time constant, the internal set-point temperature is modified over reduced operating times. The partial heating or spatially reduced heating operation is also considered by applying another correction factor, which is based on the ratio of indirectly heated area and total heated area of the building zone, on the set-point temperature. Internal gains in DIN 18599-10:2011-2 consider the heat generation from persons, machineries as well as lighting for residential buildings, and only gain from persons, machineries for non-residential buildings. The gain from lighting for non-residential buildings is calculated based on total lighting power taken from the Swiss Society of Engineers and Architects (SIA). In Table 3, the internal gains are the daily value averaged over number of normal and reduced operating days in a year. The occupancy density is a parameter applied for the domestic hot water calculation explained already in Table 1. Healthy air change rate is a parameter determining the air change rate in a building and consequently the heat transfer through ventilation.

4.2. Specific heating energy demand

The average area-specific heating demand of the whole studied district, Ludwigsburg, is 136 kWh/m²a, which means that each building in this district needs in average 136 kWh heating energy pro m² in a year to have a constant, desired temperature in the operating spaces of the building. A detailed analysis on specific heat demand is carried out in one chosen community, Hemmingen (visualized in Fig. 1). Fig. 5 shows the reduction of the specific heat demand applying two refurbishment simulation scenarios. The average savings to the status quo scenario is 58% for a high energy standard and 46% if a medium insulation standard is applied to all buildings.

The two main factors impacting both status quo and refurbishment scenarios are building age and building usage. different age structures of the buildings and different contributions of the sectors residential, public and industry, trade and commerce leads to various energy saving in municipalities. The oldest buildings have the highest demand and the highest efficiency potentials.

Within the residential sector single family buildings have the highest efficiency potential, as their specific heating energy consumption is higher than for more compact multi-family apartment buildings (see Fig. 6). The specific heating energy demand does not drop as much with refurbishment for the public building sector, where usage-related parameters result in a bigger contribution of ventilation and internal gain. Another noticeable fact was that the specific demand for industry, trade, commerce and service buildings (ITCS), considering the average year of construction of each group, they are newer that other buildings, in addition, Industries

have lower set-point temperature and annual operation days for defined in DIN 18599-10:2011-2 (See Table 3).

When analyzing the non-residential sector in more detail, it could be shown that low heating energy reduction was mainly observed for buildings with high occupant densities and thus high air exchange volumes and high internal gains (restaurants, sport facilities etc.). Industrial buildings with large surface areas, which is probably not heated largely, and no information on the specific building uses and internal processes mostly have low specific consumption values, which might underestimate the real consumption (see Fig. 7).

The results show the detailed analysis possibilities of the 3D urban modeling environment. Model calibration remains a major challenge. While the building physics and building usage data bases are well established for the residential building sector in Germany and calibration on a city quarter level has been carried out in many cases, the non-residential sector with much more varying use still needs significant work to accurately model the building performance.

5. Derivation of measures and initiatives from the analysis of results

An important part of climate protection concepts is the definition of strategies to decrease CO_2 emission. Initiatives to reduce the energy demand (e.g. of buildings) can lead to direct or indirect CO_2 savings. Another approach is to implement renewable energy supply systems to replace conventional systems, which can significantly lower CO_2 emissions too. Using the simulation results of the SimStadt urban modeling platform, it is possible to quantify the effect of CO_2 saving measures. The principle is to extract relevant outcomes of SimStadt and combine them with key indicators of particular initiatives to calculate and predict feasible energy and CO_2 savings.

Based on the calculated energy demand and the determination of objectives for the district of Ludwigsburg, several categories of measures were defined. The aim was to provide approaches for decision makers in the municipalities to take actions and support them during the execution of the climate protection concept. The measures are classified in general actions, activities in the energy supply/renewable energy sector, economic activities, actions for private buildings, for mobility, for user behavior and education, activities within the public administration sector, public relation activities and consulting or citizen participation activities. Initiatives were designed and assigned to each of the categories. Each initiative is described in detail by a profile. The profile consists of a form to enter important indicators like target group, chances/barriers of progress, costs, energy CO_2/energy savings etc. Further, key factors for costs and CO_2 savings were defined. In the
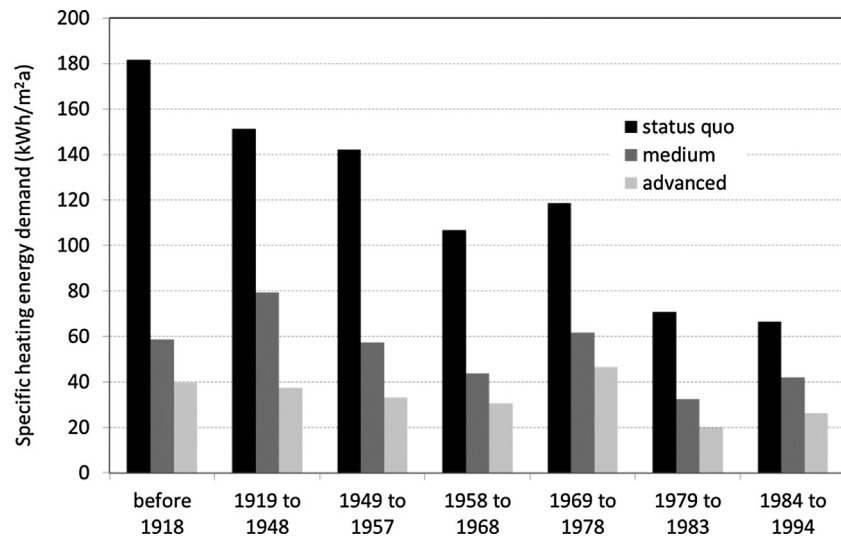
Fig. 5. Average specific heating demand for the existing building stock as well as medium and advanced refurbishment scenarios for the municipality Hemmingen.
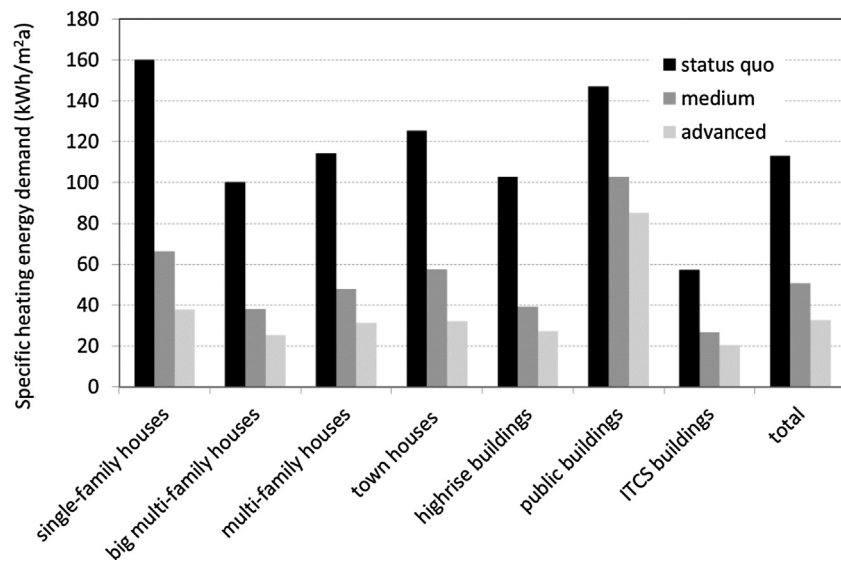

Fig. 6. specific heating demand for different building types in the municipality Hemmingen.
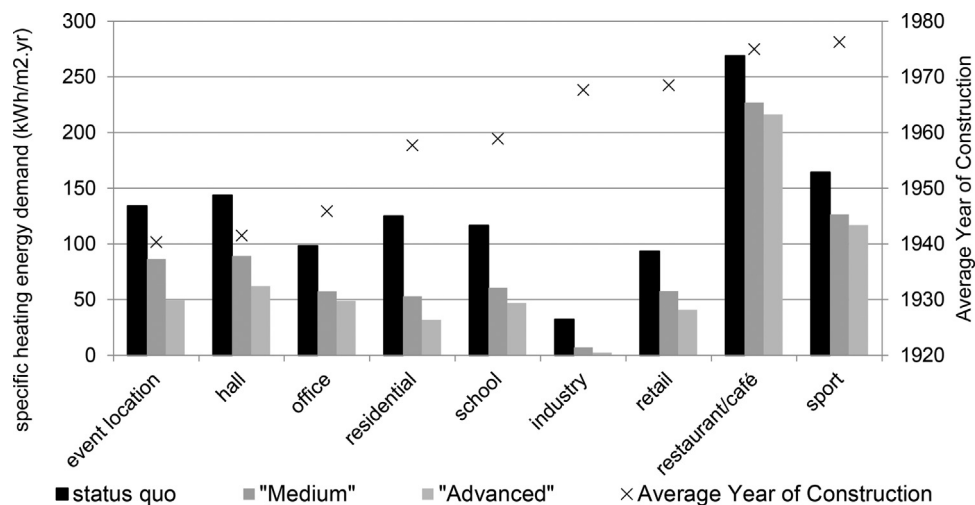

Fig. 7. Specific heating energy demand of various building types in the non-residential sector.
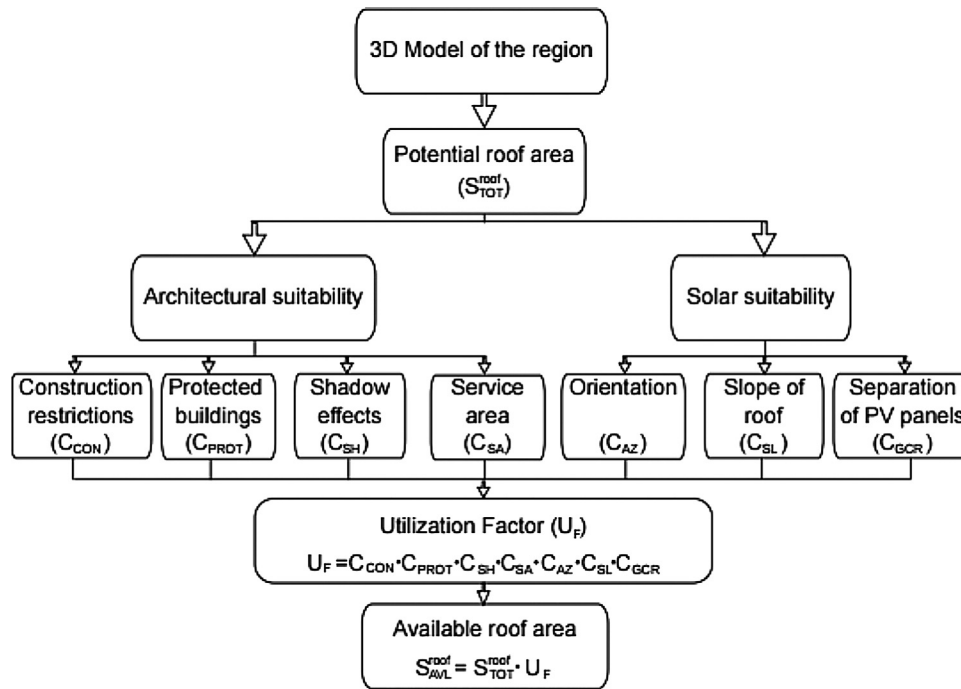
Fig. 8. Flowchart of the available roof area calculation process.

Table 4
quantified indicators by SimStadt for 1 °C reduction of set-point temperature in public buildings of Hemmingen.

Annual energy saving per each m² of a public building	32	kWh/m².a
Annual CO2 Saving per each m² of public building	7.74	kg. CO2/m².a
Annual Cost due to energy saving[a]	3	€/m²

[a] energy cost for (gas, oil burner) assumed 0.10 €/kWh.

following two of the initiatives are presented whose factors could be quantified using the urban energy model.

5.1. Example of initiative 1: reducing the desired set-point temperature by 1 °C in public sectors

Reducing the inside temperature by 1 °C in the public buildings is evaluated as one of the short-term implementing initiatives as with no need of investment it leads to a considerable saving in energy use, CO2-emission as well as energy cost. The SimStadt outputs indicates that 1 °C reducing the set-point temperature, desired temperature in normal operation of the building, and consequently the set-back temperature, the desired temperature in reduced operation of the building e.g. during night, in the public sectors results in 15% reduction of annual energy need for space heating in the Hemmingen, one of the municipalities of Ludwigsburg. According to the statistical data, Hemmingen consist of 27,104 m² public buildings containing office, school, sport location, event location and event hall. Table 4 is an overview of the main indicators of this measure. The initial set-point as well as set-back temperature of each building usage can be found in Table 3. For predicting how much energy, cost, and CO2 energy may be saved when this measure is applied, the heat demand is again calculated in SimStadt applying 1 °C less set-point and set-back temperature for these building usages.

It is indicated in Table 4 that by 1 °C reduction in the set-point and set-back temperature of public buildings, 32 kWh can be saved for each square meter of public building annually. This results in 7.74 kg CO2 saving for each square meter and annual saving of 3 Euro for each square meter.

Having applied these indicators for the entire Ludwigsburg by almost 342 ha public buildings, a considerable saving of approximately 109 GWh/a. energy for heating is resulted. This energy saving leads to an annual reduction of almost 26 kilo tone of CO2-emission and a cost saving of more than 10,000 mio. Euro. This should be considered that the distribution of public buildings, e.g. schools, offices, sport halls, etc., in Hemmingen may differ from the whole city of Ludwigsburg, and scaling up the savings to the total area of the public buildings is only the first analysis. For a more detailed analyses it is recommended to re-simulate the whole Ludwigsburg with new set-point and set-back temperature.

5.2. Example of initiative 2: using the photovoltaic potential

As an exemplary initiative the installation of PV systems has to be accelerated to better exploit the existing technical potential, which is defined as the implementation of PV panels on all available surface, or at least the economic potential, which considers only buildings with solar yields and roof area above certain threshold values. In this study we have assumed the roof areas greater than 40 m² and with minimum average annual insolation of 1100 kWh/m².a. To support this process, the simulated potential shall be communicated activating energy consultants, project managers and property owners of the district. The politically agreed target is to reduce CO_2 emissions by 2% every year. This measure was assigned to the energy supply/renewable energies activities.

Using the 3D models, all buildings in the district are analyzed for their roof area potential for photovoltaic electricity generation. A series of reduction coefficients are taken into account, which are applied to each building individually and are essential for an accurate solar potential assessment. Construction restrictions, separation of the PV panels and other issues are considered in order to quantify the total available area which can be used to install the PV modules (see Fig. 8). Further explanations of these factors are included in [29]. A summary of the chosen coefficients for the present study is shown in Table 5.

Once the available roof area is known, the technical PV potential of the entire region is calculated by simulating the irradiance on

Table 5
Summary of the used reduction coefficients.

Reduction factor	Value
CCON	Flat roofs: 0.8
	Tilted roofs: 0.9
CPROT	1
CSH	Flat roofs: 0.7
	Tilted roofs: 0.8
CSA	Flat roofs: 0.97
	Tilted roofs: 1
CAZ	1 (considered in SimStadt)
CSL	1 (considered in SimStadt)
CGCR	Flat roofs: 0.46
	Tilted roofs: 1

Table 6
Summary of the results obtained for the photovoltaic generation.

Variable	Result	Description
$E_{PV}^{Technical}$	1318 [GWh/a]	Technical PV potential calculated by SimStadt
$E_{PV}^{Economic}$	958 [GWh/a]	Economic PV potential calculated by SimStadt
B_t	157 724 [buildings]	Total number of buildings simulated in SimStadt
$E_{Building}^{Technical}$	8355 [kWh/a]	Technical PV potential per building
P_{PV}	1642 [MWp]	Total PV nominal power calculated by SimStadt

each surface using INSEL models (based on the Hay sky model for diffuse irradiance calculation) and by taking into account the efficiency of the PV system, which is 16%. The economic PV potential is also calculated, considering a minimum irradiance threshold of 1000 kWh/m²a, and a minimum roof area of 40 m² for each building. It should be noted that not every building of the region could be simulated within the automated urban simulation workflow, as the geometry preprocessor discards buildings not properly defined, for example if the polygons are not closed. The percentage of simulated buildings is 89%, which is considered high enough for the accuracy of the results, especially as ratios of photovoltaic generation to consumption are of main interest. A summary of the obtained results for the region is shown in Table 6.

In some municipalities more than 100% of the annual electricity demand can be covered by PV modules on all roof areas (technical potential), while others have a lower PV fraction (see Fig. 9). The average technical potential for the entire region is 76%. The calculation of the economic PV potential using insolation thresholds to select only south facing roofs and minimum roof areas lead to an average value of 55% of covered electricity demand for the entire region.

As previously stated, the plan is to reduce 2% of the CO_2 emissions every year. The key indicator of this measure is the annual percentage of buildings which should be equipped with PV for achieving this reduction "Bred". In order to do that, the annual required PV generation can be calculated from the 2% CO_2 savings divided by the CO_2 electricity emission factor.

$$E_{red} = \left(\frac{CO_{2,tot}}{CO_{2,spec.emission}} \right) \times 0.02 \left[kWh/a \right] \qquad (3)$$

Where $CO_{2,tot}$ is the total annual CO2 emissions and $CO_{2,spec.emission}$ the emission coefficient per kWh of the substituted PV electricity in Germany. This factor considers the average CO2 of the life-cycle of PV panels as well. Depending on the PV system, the production technology, the local solar irradiance, as well as weather it is applied locally or it is fed into the grid the CO2 emission through the PV life cycle may differ. A ranges from 39 to 110 gCO₂/kWh has been found in the study of Jungbluth [31]. In this study the average value, 75 gCO₂/kWh, is applied.

Table 7
Calculation process of the annual percentage of buildings to reach 2% CO2 savings.

Variable	Result	Description
$CO_{2,tot}$	965,000 [t CO_2/a]	Annual CO_2 emissions.
$CO_{2,spec.emission}$	535 [gCO2/kWh-El.-mixed]-[a]74 [gCO2/kWh-El.-PV][b]	Coefficient of the substituted CO_2 of PV installations in Germany (considering Life-cycle of PV)
E_{red}	40,115 [MWh/a]	Required yearly PV production to achieve 2% savings.
B_{red}	3.04 [%]	Annual percentage of buildings to be equipped with PV to reach 2% CO_2 savings.

[a] Source: [30].
[b] Source: [31], in this study, the greenhouse gas emissions for PV range from 39 to 110 g CO2 eq/kW h. here the average is applied.

Table 8
Listing of economic indicators and their parameters for the technical PV potential of the region.

Variable	Result	Description
$E_{PV}^{Technical}$	1 318 [GWh/a]	Technical PV potential calculated by Simstadt.
C_{elec}	0.22 [€/kWh]	Electricity price per kWh (Experience value).
C_{ft}	0.1231 [€/kWh]	Feed-in tariff for small PV facilities [32]
C_{System}	1280 [€/kWp]	Average price for the installation of 1 kWp PV [33]
F_{Self}	30 [%]	Percentage of the electricity used for self-consumption.
P_{PV}	1642 [MWp]	Total nominal power calculated by SimStadt.
C_t	2101 [M€]	Total investment costs.
A_s	201 [M€]	Total annual savings.

Since the annual necessary energy savings and the PV potential per building are known, the percentage of buildings to be equipped with PV is then calculated from:

$$B_{red} = \frac{\left(\frac{E_{red}}{E_{Building}^{Technical}} \right)}{B_t} \times 100 \, [\%] \qquad (4)$$

The achieved results are shown in Table 7:

An economic analysis of this measure for the whole region was also done to assess the measure. On the one hand, the annual savings "A_s" [€/year] by avoiding grid electricity costs was identified. For this calculation, a 30% of self-consumption for the region was assumed [12], the other 70% obtain a feed-in tariff. The annual savings can be compared with the total investment costs "C_t" (€).

$$A_s = E_{PV}^{Technical} \left(F_{Self} C_{elec} + \left(1 - F_{Self} \right) C_{ft} \right) \qquad (5)$$

$$C_t = P_{PV} \times C_{System} \qquad (6)$$

After extracting the required results from SimStadt, the indicators shown in Table 8 for the whole region could be calculated.

The economic analysis in order to achieve the 2% reduction of CO_2 emissions, using the same costs and coefficients is presented in Table 9.

As a result, a 2% reduction of the CO_2 emissions of the region can be achieved with an investment of 64 million € (180 €/inhabitant) by implementing PV panels in 3.04% of the buildings of the region. This compares to annual savings of around 6 million € per year, resulting in a payback period of about 10 years.

6. Conclusions

Urban 3D models enriched with data on building's construction, thermal properties and functions, like residential or office,
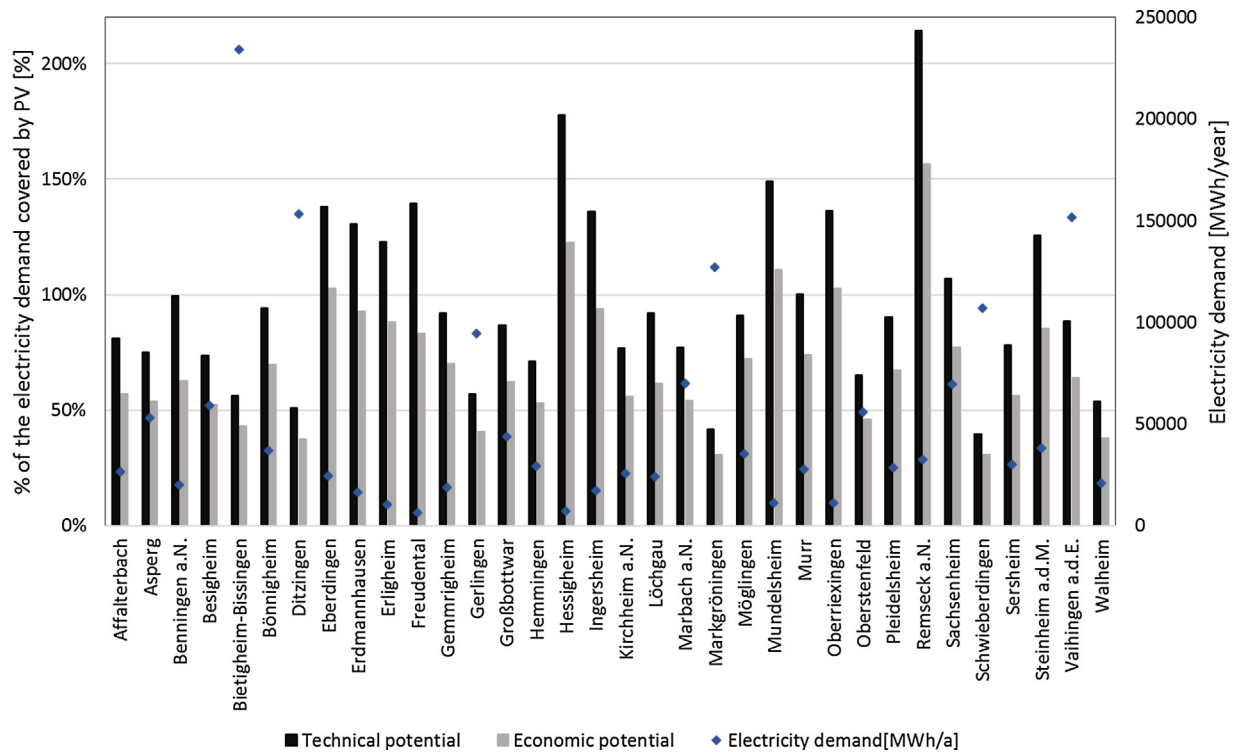
Fig. 9. Electricity demand and technical and economic PV potential for all the municipalities.

Table 9
Listing of economic indicators for the 2% CO2 emissions reduction.

Variable	Result	Description
E_{red}	40 [GWh/a]	Required yearly PV production to achieve 2% savings.
P_{red}	50 [MWp]	Approximate nominal power needed to achieve 2% savings.
C_{red}	64 [M€]	Total investment costs.
A_{red}	6 [M€]	Annual savings.

offer excellent support for establishing climate protection concepts by allowing to quantify measures to improve energy efficiency and integrate renewables. In this study, SimStadt, an automated platform, has been employed for developing a climate protection concept for the case study of Ludwigsburg with almost 177,000 residential and non-residential buildings. SimStadt is applied to quantify the indicators such as CO2 emission reduction, energy saving and energy cost savings for energy concept's measures and initiatives. The heat demand of the buildings is calculated building by building, which built the bases of several measures for the climate protection concept. For example, it is shown that for Ludwigsburg with approximately 342 ha public buildings, 1 °C reduction in the set-point temperature and set-back temperature of the public buildings results in 109 GWh annual energy saving, corresponds to more than 10,000 mio. Euro. Moreover, applying the highest standard refurbishment scenario, the heating energy demand of the building sector in the studied case study could be reduced by up to 58% or by 46% applying medium level of insulation. The PV Potential of each individual building is also calculated by this platform and the coverage of electricity demand of Ludwigsburg by this PV potential is investigated.

As it is shown many of the parameters influencing the measures' indicators such as the heated area, heating energy demand, PV-Potential etc. are highly dependent on the 3D model of the city.

Therefore, the more accurate and up-to date the 3D model is, the more accurate the indicators are quantified and analyzed. In other words, if the recent changes in the buildings' status (for example new buildings, demolished buildings, expanded buildings), as well as buildings' function (for example using churches for cultural activities, or changing an office to a residency) can be available, the analyses of the indicators can be more accurate. However, quantifying and analyzing several indicators for developing a climate protection concept in an urban scale requires many efforts. Therefor employing an urban analyzing platform, like SimStadt, still offers a good opportunity for municipalities.

The total heat demand of the residential buildings calculated by SimStadt is also compared to the real heat consumption of residential buildings for each municipality of Ludwigsburg. It is indicated that, it is very challenging to get detailed and reliable municipal consumption data to seriously validate the simulation results. Sometimes the measured gas consumption in a big scale of a municipality can even be not trustable, as for our case study we had two different source of data with a deviation of 50% for some municipalities. This problem bolds out the advantages of an automated platform for calculating heat demand in big scales such as urbans or cities, especially where no measured consumption data is available or difficult to evaluated or even a prediction for a new scenario is needed. (For example heat demand after several refurbishment scenarios.) It is shown that for our case study, on an aggregated municipal level, the deviations between measured and simulated gas consumption was between 20 and 30% or sometimes higher, where the input data like refurbishment data is not fully available. However, previous validation works at scale of building-blocks with good monitoring data quality demonstrates that the error between consumption and modeled yearly heating energy demand can be less than 10%. Therefore, this is recommended to the municipalities to pay a greater attention on an intelligent data collection with particular focus on the building's year of construction and refurbishment status in their databases.

The 3D modeling allows accurate simulations of renewable electricity generation from photovoltaics, as well. It could be shown that in the studied region 77% of the electricity consumption could be technically covered by photovoltaics. Using irradiation thresholds to select only south facing roofs and minimum roof areas leads to an economic PV potential which covers 55% of the electricity consumption. In order to obtain these results, the present study makes use of several reduction coefficients such as shading. The accuracy of the proposed method could be improved by using a solar radiation model that accounts for the effects of the obstructions caused by surrounding buildings instead. Furthermore, in order to obtain a 2% annual carbon reduction in the studied region, 3.04% of all buildings would have to install PV systems annually at a total investment of 64 million Euros or 180 € per inhabitant. At annual revenues of 6 million Euros this measure seems feasible and economically viable.

Although this study is limited to a concrete regional case study, the replication potential of the result is high as the work flow and result generation is completely automated. The requirements for replication of the results are:

– 3D models of urban areas in CityGML format. In case the CityGML data in LoD1 format is available, the 3D city model should contain valid Solid geometry per building. For LoD2 models boundary surfaces such as wall, roof and ground surfaces are also mandatory.
– basic attribute data such as year of construction and building usage

If these requirements are met, the methodology can and has been applied to cities as large as New York with more than one million buildings.

All in all, using the automated workflows for urban energy modeling makes it possible to establish and evaluate policies on a municipal and regional level. With reliable input data such as an up-to-date 3D model as well as buildings construction and usage data, this work shows that building efficiency, refurbishment scenarios and renewable integration can be well quantified to support decision making for developing climate protection concepts. It is even more worthy where achieving current state of consumption of the buildings is challenging or different scenarios, e.g. refurbishment scenarios, is in a great interest.

Acknowledgements

References

[1] M.M. Betsill, H. Bulkeley, Transnational networks and global environmental governance: the cities for climate protection program, Int. Stud. Q. 48 (2) (2004) 471–493, http://dx.doi.org/10.1111/j.0020-8833.2004.00310.x.

[2] R. Evans, S. Guy, S. Marvin, Views of the city: multiple pathways to sustainable transport futures, Local Environ. 6 (2) (2001) 121–133, http://dx.doi.org/10.1080/13549830120052773.

[3] B. Howard, L. Parshall, J. Thompson, S. Hammer, J. Dickinson, V. Modi, Spatial distribution of urban building energy consumption by end use, Energy Buildings 45 (2012) 141–151, http://dx.doi.org/10.1016/j.enbuild.2011.10.061.

[4] O.G. Santin, L. Itard, H. Visscher, The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock, Energy Buildings 41 (11) (2009) 1223–1232, http://dx.doi.org/10.1016/j.enbuild.2009.07.002.

[5] K.J. Baker, M.R. Rylatt, Improving the prediction of UK domestic energy-demand using annual consumption-data, Appl. Energy 85 (6) (2008) 475–482, http://dx.doi.org/10.1016/j.apenergy.2007.09.004.

[6] J. Keirstead, M. Jennings, A. Sivakumar, A review of urban energy system models: approaches, challenges and opportunities, Renew. Sustain. Energy Rev. 16 (6) (2012) 3847–3866, http://dx.doi.org/10.1016/j.rser.2012.02.047.

[7] L.G. Swan, I.V. Ugursal, Modeling of end-use energy consumption in the residential sector: a review of modeling techniques, Renew. Sustain. Energy Rev. 13 (8) (2009) 1819–1835, http://dx.doi.org/10.1016/j.rser.2008.09.033.

[8] S. Heiple, D.J. Sailor, Using building energy simulation and geospatial modeling techniques to determine high resolution building sector energy consumption profiles, Energy Buildings 40 (8) (2008) 1426–1436, http://dx.doi.org/10.1016/j.enbuild.2008.01.005.

[9] M. Kavgic, A. Mavrogianni, D. Mumovic, A. Summerfield, Z. Stevanovic, M. Djurovic-Petrovic, A review of bottom-up building stock models for energy consumption in the residential sector, Build. Environ. (2010), http://dx.doi.org/10.1016/j.buildenv.2010.01.021, pp. 1683–1697.

[10] B. Wauman, H. Breesch, D. Saelens, Evaluation of the accuracy of the implementation of dynamic effects in the quasi steady-state calculation method for school buildings, Energy Buildings 65 (2013) 173–184, http://dx.doi.org/10.1016/j.enbuild.2013.05.046.

[11] D. Zehe, A. Knoll, W. Cai, H. Aydt, SEMSim cloud service: large-scale urban systems simulation in the cloud, Simul. Modell. Pract. Theory 58 (2015) 157–171, http://dx.doi.org/10.1016/j.simpat.2015.05.005.

[12] S.J. Quan, Q. Li, G. Augenbroe, J. Brown, P.P.-J. Yang, A GIS-based energy balance modeling system for urban solar buildings, Energy Procedia 75 (2015) 2946–2952, http://dx.doi.org/10.1016/j.egypro.2015.07.598.

[13] G. Masson, J.I. Briano, M.J. Baez, Review and Analysis of Pv Self-Consumption Policies, 2016, Retrieved from http://iea-pvps.org/index.php?id=353andeID=dam_frontend_pushanddocID=3066.

[14] J. Tomaschek, R. Kober, U. Fahl, Y. Lozynskyy, Energy system modelling and GIS to build an integrated climate protection concept for Gauteng province, South Africa, Energy Policy 88 (2016) 445–455, http://dx.doi.org/10.1016/j.enpol.2015.10.041.

[15] Y. Yin, S. Mizokami, K. Aikawa, Compact development and energy consumption: scenario analysis of urban structures based on behavior simulation, Appl. Energy 159 (2015) 449–457, http://dx.doi.org/10.1016/j.apenergy.2015.09.005.

[16] A. Strzalka, U. Eicker, V. Coors, J. Schumacher, Modeling Energy Demand for Heating at City Scale, 2010, Retrieved from http://www.hft-stuttgart.de/Forschung/Kompetenzen/zafh/Publikationen/publikationen_download/2010/Strzalka_A_Eicker_Coors_Schumacher_SimBuild_2010.pdf.

[17] D. Carrión, A. Lorenz, T.H. Kolbe, Estimation of the Energetic Rehabilitation State of Buildings for the City of Berlin Using a 3D City Model Represented in Citygml, 2010, Retrieved from http://www.isprs.org/proceedings/xxxviii/4-w15/Paper_ISPRS/Oral/6_3DGeoInfo2010_157_Carrion_Energetic_Rehabilitation.pdf.

[18] R. Kaden, T. Kolbe, City-Wide Total Energy Demand Estimation of Buildings using Semantic 3D City Models and Statistical Data, in: ISPRS 8th 3DGeoInfo Conference, Istanbul, Turkey, 27-29 November, 2013.

[19] R. Nouvel, C. Schulte, D. Pietruschka, V. Coors, CityGML-based 3D City Model for Energy Diagnostics and Urban Energy Policy Support, Chambéry, France, 2013, Retrieved from http://www.ibpsa.org/proceedings/BS2013/p_989.pdf.

[20] F. Prandi, U. Di Staso, M. Berti, L. Giovannini, P. Cipriano, R. De Amicis, Hybrid approach for large-scale Energy Performance estimation based on 3D city model data and typological classification, Proceedings of the 1st ICA European Symposium on Cartography (2015).

[21] G. Gröger, L. Plümer, CityGML ? Interoperable semantic 3D City Models, ISPRS J. Photogramm. Remote Sens. Vol. 71 (2012), pp. 12–33.

[22] T.H. Kolbe, Representing and exchanging 3D city models with CityGML, Lecture Notes in Geoinformation and Cartography (2009) 15–31, http://dx.doi.org/10.1007/978-3-540-87395-2_2.

[23] R. Nouvel, K.-H. Brassel, M. Bruse, E. Duminil, V. Coors, U. Eicker, D. Robinson, SimStadt, a New Workflow-Driven Urban Energy Simulation Platform for CityGml City Models, 2015 (Lausanne. Retrieved from https://infoscience.epfl.ch/record/213437/files/9_NOUVEL1187.pdf).

[24] Directive 2007/2/EC of the European Parliament and of the Council, Official Journal of the European Union § Establishing an Infrastructure for Spatial Information in the European Community, INSPIRE, 2007.

[25] L. Dörrzapf, B. Mušič, M. Schrenk, W.W. Wasserburger, SUNSHINE: Smart UrbaN ServIces for Higher eNergy Efficiency, 2013, http://dx.doi.org/10.1553/giscience2013s18 (Rome, Italy).

[26] F. Biljecki, G.B.M. Heuvelink, H. Ledoux, J. Stoter, Propagation of positional error in 3D GIS: Estimation of the solar irradiation of building roofs, Int. J. Geog. Inf. Sci. 29 (12) (2015) 2269–2294, http://dx.doi.org/10.1080/13658816.2015.1073292.

[27] R. Nouvel, M. Zirak, V. Coors, U. Eicker, The influence of data quality on urban heating demand modeling using 3D city models, Comput. Environ. Urban Syst. 64 (2017) 68–80.

[28] Institut Wohnen und Umwelt (IWU), TABULA – EU Project, 2013 (Retrieved June 29, 2016, from http://www.iwu.de/1/forschung/energie/completed-projects/tablua/).

[29] L. Romero Rodríguez, E. Duminil, J. Sánchez Ramos, U. Eicker, Assessment of the photovoltaic potential at urban level based on 3D city models: a case study and new methodological approach, Sol. Energy 146 (2017) 264–275, http://dx.doi.org/10.1016/j.solener.2017.02.043.

[30] P. Icha, G. Kuhs, Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 bis 2015, 2016, Retrieved from

http://www.umweltbundesamt.de/en/publikationen/entwicklung-der-spezifischen-kohlendioxid-2.

[31] N. Jungbluth, Life cycle assessment of crystalline photovoltaics in the Swiss ecoinvent database, Prog. Photovolt: Res. Appl. 13 (2005) 429–446, http://dx.doi.org/10.1002/pip.614.

[32] Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen, Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post Und Eisenbahnen, 2016 (Retrieved June 16, 2016, from http://www.bundesnetzagentur.de/DE/Home/home_node.html).

[33] Fraunhofer ISE, Photovoltaics Report, 2016 (June, Retrieved from https://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf).